Effects of Forest Biomass Use on Watershed Processes in the Western United States

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ABSTRACT

As society looks to our nation's forests as sources of energy, there is a risk of increased runoff and erosion. This report gives an overview of watershed processes, discusses the impacts of biomass removal on those processes, provides some guidelines to minimize adverse impacts, and describes an approach for estimating the effects of biomass removal on soil erosion.

Keywords: energy, wood fuel, timber harvest

With increasing energy costs, society is looking at alternative energy sources. One potential energy source that is currently underused in the United States is forest biomass (Rummer et al. 2003). However, if forests are subject to a significant increase in biomass removal for energy production, then it is possible that hydrologic resources may be adversely affected.

This report describes forest hydrologic processes, looks at the impacts of biomass use on those processes, and then describes an approach for watershed analysis to quantify those impacts. Although many of the principles discussed in this article apply to all forests, this article focuses on forest watershed processes common in the western United States.

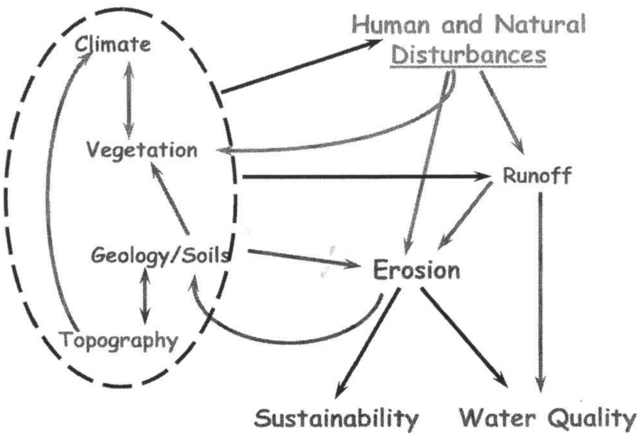

Figure 1. Diagram showing complex interactions that drive forest watershed processes.

Hydrologic Processes

Hydrologic processes in forested ecosystems of the western United States are complex (Figure 1) (Luce 1995). Climate, topography, geology, soils, and vegetation all interact to affect runoff and erosion rates. Erosion influences onsite forest soil productivity (Page-Dumroese et al. 2000) and offsite water quality (Elliot and Audin 2006). These processes are driven by natural disturbances such as wildfire and severe weather that can lead to flooding, landslides, debris flows, etc. Human disturbances that accelerate erosion include intentional and accidental fires, timber harvest, grazing, road and building construction, and other land uses.

Hydrologic processes can be divided into vertical water movement (including precipitation, snow accumulation and melt, infiltration, and deep seepage) and lateral flow (Figure 2) (Fangmeier et al. 2006). Once water has entered the soil, it can move laterally either as shallow lateral flow through the forest duff layer or through surface soil horizons and macropores. It may also move laterally as groundwater. Groundwater impacts may be limited at the hillslope scale, but they become important in larger watersheds.

Infiltration rates depend on soil properties, such as the soil surface cover and soil water content. If the soil is not saturated, then the infiltration rate is a function of water content and soil properties, such as noncapillary porosity, texture, bulk density, water repellency, and surface cover. If the soil is saturated, then the infiltration rate will be limited by the saturated hydraulic conductivity of the soil (Luce 1995).

Forest vegetation can play a significant role in forest hydrology (Hubbart 2007). Evapotranspiration varies with age and condition of vegetation, with very young and mature forests tending to have lower transpiration rates, whereas healthy growing forests have the greatest rates. In forests where snow dominates hydrology, trees have several significant influences on snow hydrology. During the winter, trees can intercept a significant amount of snowfall. Hubbart (2007) measured up to about 200 mm of snow water equivalent less under a canopy than in a clearing in northern Idaho. Troendle et al. (2006) stated, "In coniferous forests in the cold snow zone, one generally can expect that 25–35% of the winter snowpack will be intercepted

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This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; square kilometers (km^2): 1 km^2 = 0.3861 mi^2; hectares (ha): 1 ha = 2.47 ac; metric ton (Mg, megagram, or metric tonne): 1 Mg = 2204 lb.

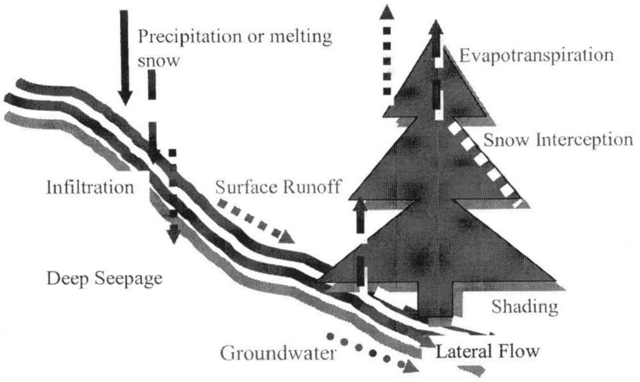

Figure 2. Dominant hydrologic processes on a forest hillslope.

and lost to the atmosphere by some combination of sublimation and evaporation." In a compilation of studies in the Pacific Northwest, where rain is more common in the winter, interception losses ranged from 10 to 30% (Moore and Wondzell 2005) and approximately 20% in northwestern California in another study (Reid and Lewis 2007). Frequently, this intercepted snow sublimates (changes from solid water to water vapor) and never reaches the ground. Thus, the snow available to melt, infiltrate, or run off can be reduced by up to 200 mm per year in mature forests. Trees also can affect the distribution of snow, with greatest accumulations of snow on the edges of clearings, and under windy conditions, the least accumulation of snow is found in the middle of large clearings. In the spring, trees on southerly facing slopes can shade snow on the ground, delaying the snowmelt from early spring (February to March) until late spring (April to May) (Troendle et al. 2006, Hubbart 2007). Early melt rates driven by solar energy tend to be slower than later melt rates driven by warm air temperatures. A final major effect of vegetation on hydrologic processes is that it generates surface residue cover. In forests, this is generally referred to as duff, the layer of organic material made up of needles, leaves, branches, and larger organic debris (tree trunks and large branches) at different stages of decomposition (Robichaud and Miller 1999). This layer plays a major role in enhancing infiltration, reducing surface runoff, reducing soil evaporation, and contributing to lateral flow (Luce 1995, Pannkuk and Robichaud 2003).

In watersheds greater than 5 km^2, hillslope processes become less important (Ziemer and Lisle 1998). Runoff in mountain forested terrain is dominated by lateral flow and groundwater because of high infiltration capacities and rapid lateral flow (Dun et al. 2009). High flows are influenced mainly by weather, including precipitation amounts, intensities, and durations, and snowmelt rates. Most high flows are associated with prolonged periods of rainfall and/or a combination of rain on snow, which saturate soils, so that the only place the water can go is into the stream network (e.g., McClelland et al. 1997).

Impacts of Biomass Use

Biomass removal can cause considerable disturbance within a watershed. Logging traffic can cause soil compaction, particularly if soils are wet, and duff disturbance, exposing mineral soil (Powers et al. 2004, Robichaud et al. 2007). These disturbances contribute to reduced infiltration and increased surface erosion. Harvesting trees for biomass has the potential for greater onsite impacts than common with current forest harvesting practices. For example, mechanical harvesting of many small-diameter trees per hectare requires machine traffic over much of the area. In one northern California study, about ⅓ of the harvested area was highly disturbed, ⅓ moderately disturbed, and only ⅓ relatively undisturbed (Nakamura 2004).

Compaction

If woody biomass is removed using wheeled or tracked equipment when soils are wet and soil strength is low, soil compaction is likely to occur (Johnson et al. 2007). Moderate and high disturbance from harvesting can measurably increase soil bulk density and soil strength, but it is not clear what impact that increase will have on tree growth. Powers et al. (2004) have reported preliminary results from a long-term soil productivity study indicating that soil compaction increases bulk density and soil strength on loam soils but has only slight effects on biomass productivity over 10 years. Compacted soils may take many decades to recover to undisturbed conditions (Froehlich et al. 1985). Processes that reduce compaction include wetting and drying in soils that are high in clay and freezing and thawing in climates where temperatures drop below freezing before there is a snow cover. Growth of plant roots can open up passages that become macropores when the root dies. Compacted soils tend to resist root penetration, however, slowing this form of recovery. In most forest environments, none of these processes occur quickly, and it is not uncommon to observe compaction many decades after the forest operation that created the compaction (Alexander and Poff 1985). Compaction reduces infiltration rates (Johnson and Beschta 1980, Cafferata 1983), and in all but sandy soils, it reduces the amount of soil water available for plant growth (Zou et al. 2000). These problems are most detrimental in drier forests, where lack of water restricts forest growth during part of the growing season.

Duff Integrity

Forest duff is not a static material but is rather a layer that is constantly decomposing and being replenished by needles, leaves, and branches from forest vegetation (Luce 1995, Robichaud and Miller 1999). As woody biomass is removed, there will be fewer trees to generate organic material to replenish duff material that is lost through decomposition. This is particularly true in warmer climates, where decomposition may exceed replenishment rates, but it is less common in cooler, drier parts of the western United States. Under some conditions, the duff cover will decline through decomposition for several years until vegetation regeneration is sufficient to restore the duff cover to what it was before the disturbance. In addition, the physical process of removing biomass can displace the duff layer, leaving bare mineral soil exposed to the erosive forces of wind, rain, and overland flow.

Infiltration

Compaction and loss (or large-scale displacement) of duff will reduce soil infiltration rates, leading to increased surface runoff and hillslope erosion (Robichaud et al. 1993, 2007). In some climates, frozen soils can also significantly decrease infiltration rates, particularly if the insulating duff layer has been disturbed by mechanical operations. Generally, only a small fraction of runoff from undisturbed forests is surface runoff (Sloan and Moore 1984). Where surface runoff does occur, it is frequently associated with areas that are heavily disturbed, such as roads and skid trails. Small changes in

Table 1. Typical best management practices to follow to minimize impacts of biomass use.

Practices
Onsite practices
Minimize mineral soil exposure
Minimize turnarounds with equipment
Use designated skid trails
Use harvesters with longer booms
Maintain undisturbed buffers along streams
Avoid working when soils are wet
Winter logging may work
Avoid dragging logs
Lift ends with skidders
Use grapple skidders or forwarders
Minimize the amount of traffic
Mitigate skid trails
Install frequent water bars
Cover trails with slash
Use low ground pressure equipment
Bigger tires or tracks
Note: Smaller vehicles make more trips
Road network management
Remove unwanted road segments, especially culverts and stream crossings
Outslope whenever safe with frequent dips
Keep insloped ditches stable with coarse gravel or vegetation
Install cross drains or ditch relief culverts where there is adequate vegetated buffer available between the road and the stream
Consider the fate of all road drainage
Install ditch relief culverts about 50 ft before stream crossings
Use gravel (or asphalt) within 50 ft of live water crossings
Avoid ruts
Close roads when wet
Use gravel
Blade regularly
Monitor culverts to prevent blockage and diversion
Locate roads to minimize sediment delivery to streams

infiltration are unlikely to cause any major changes in surface runoff rates. Any increase in surface runoff will likely be accompanied by a decrease in lateral flow (Crabtree 2007), minimizing the effects of changes in infiltration on runoff (Figure 2). These changes in infiltration can, however, change lag times and increase instantaneous peak discharges for small storms in small watersheds (Sendek 1985).

Surface Erosion

Compaction, loss of surface cover, and a small increase in surface runoff can lead to a significant increase in erosion (Robichaud et al. 1993, Pannkuk and Robichaud 2003). Splash erosion and runoff are minimal when surface cover protects mineral soil from raindrop impact. Raindrop splash erosion, rill erosion, and gully erosion are all directly affected by surface runoff rates (Fangmeier et al. 2006).

Wildfire

Wildfire is common in western watersheds, occurring at intervals ranging from 20 to more than 300 years (McDonald et al. 2000). In many forest watersheds, the greatest source of sediment is associated with erosion following wildfire (Elliot 2006, Lavine et al. 2006). Peak runoff rates and erosion rates following wildfire are 10 to 1,000 times greater than from undisturbed forests (Elliot 2006, Lavine et al. 2006, Robichaud et al. 2007). One of the benefits of harvesting biomass is that the severity or frequency of wildfire may be reduced (Elliot 2006, Graham et al. 2007).

Roads

After wildfire, the second greatest source of sediment in most forest watersheds is the road network (MacDonald et al. 2004, Elliot 2006). A road network is necessary to remove biomass. Many forest roads were built to lower standards in the last century and are now covered with grass and shrubs. Forest roads are highly compacted by design, and they retain this compaction for decades (Luce 1997, Foltz et al. 2009). The impact of overgrown "legacy" roads on erosion may be minimal or significant, depending on site-specific conditions. In northern California and the Pacific Northwest, legacy roads subjected to large storm events can produce substantial sediment delivery to stream channels from mass failures associated with poorly constructed road fills, as well as catastrophic failure of unmaintained stream crossings (Elliot et al. 1994, Cafferata and Spittler 1998, Madej 2001, Gerhardt and Strohmeyer 2008). Another concern with roads is that they can concentrate flow on a hillside and cause channel initiation and erosion where previously there had been no channel (Elliot and Tysdal 1999). Unmaintained roads may also cause localized increases in surface runoff. If overgrown roads are opened up to allow access for removing biomass for fuel, surface erosion rates from these roads will likely increase by a factor of 100 (Foltz et al. 2009).

Some watersheds have high road densities (kilometers of road per square kilometer of watershed), a legacy of past logging practices. Road removal may be considered to offset the effects of removing biomass. For example, removing a kilometer of road may offset the increase in erosion from several hundred hectares of forest that was harvested for biomass. Road removal studies have shown that road treatments can reduce the long-term sediment production from decommissioned roads but that there will be short-term sediment impacts due to channel adjustments following crossing removal (Madej 2001, Keppeler et al. 2007, Foltz et al. 2008).

Water Yield

Runoff from forested watersheds is increasingly needed for societal uses such as irrigation, domestic and industrial consumption, fisheries, and other wildlife conservation. Removing trees reduces rain and snow interception and evapotranspiration, making more water available for other uses (Troendle et al. 2006, Hubbart 2007). In the case of evapotranspiration, the benefits will likely last a few years, as younger forests can have higher evapotranspiration rates than mature forests (Keppeler and Ziemer 1990, Moore and Wondzell 2005). In snow-dominated watersheds, canopy removal may decrease snow interception for several decades (Troendle et al. 2006). Differences in interception between logged and unlogged areas are likely to explain the majority of the observed increases in larger winter peak flows, when transpiration is at its annual minimum. Forest canopy removal can also influence rain-on-snow floods in some areas. For example, Ziemer and Lisle (1998) and Moore and Wondzell (2005) both report that clearcutting exacerbated some rain-on-snow floods in northern California.

Increased runoff from increased snowpack is not seen every year, however. The increased flows generally occur in wet years, when there are likely more than adequate flows in streams and rivers already. In dry years, when water may be limited, increases in runoff associated with timber removal are unlikely. There is also some concern that altering flow regimes from forests could alter channel shapes and adversely affect the aquatic environment (Elliot and Audin 2006). In addition, in larger watersheds, Ziemer (1987) and Hubbart (2007) both reported that total water yield increases resulting from management were small and likely not measurable.

Table 2. Example of the erosion part of a watershed analysis.

Background	Erosion (Mg/ha)	Biomass removal	Erosion (Mg/ha)
Wildfire (10 Mg/ha ÷ 50 years)	0.20	Wildfire (5 Mg/ha ÷ 100 years)	0.05
Forest (every year)	0.05	Forest (every year)	0.05
Essential roads	0.15	Essential roads	0.15
Unneeded roads	0.05	Unneeded roads removed	0.00
Brushed-in roads	0.00	Additional roads opened	0.05
Background	0.45	Biomass removal (1 Mg/ha ÷ 50 years)	0.02
		With treatment	0.32

Summary of Guidelines

There are two general guidelines for minimizing the watershed impacts of removing biomass. Managers should seek to minimize duff layer and soil disturbance, and the road network should be well maintained and kept to a minimum. Best management practices (BMPs) have been developed by most state and federal agencies to follow these guidelines (Seyedbagheri 1996, Keller and Sherar 2003). A partial list of these BMPs is provided in Table 1.

An Approach to Watershed Analysis

In some cases, forest managers may be required to carry out a watershed impact analysis before proceeding with a biomass removal project. Federal agencies are required by law to complete such an analysis, and state or local jurisdictions may require such a plan for private land owners. This analysis should compare the watershed impacts of biomass removal to naturally occurring processes. There are a number of different tools available for such an analysis (Elliot and Audin 2006). For example, Rocky Mountain Research Station (RMRS) (2005) has developed one simplified method to provide a framework for such an analysis. This method incorporates four steps. The first step in a watershed analysis is to estimate the erosion associated with natural processes. There are generally two conditions to consider for erosion from natural processes: the undisturbed condition and the erosion associated with wildfire. Generally, erosion associated with an undisturbed condition is minimal. An "average" annual effect of wildfire can be estimated by dividing the estimated erosion the year following wildfire by the estimated number of years between wildfires in that forest (Elliot 2006). For example, a manager may estimate wildfire erosion to be 10 t/ha, but as it only occurs once every 100 years, the "average" annual erosion is 0.1 Mg/ha. The erosion from an undisturbed forest can be estimated and added to the average wildfire erosion value to estimate wildfire contribution to the natural erosion rate. For example, an undisturbed forest erosion rate may be about 0.05 Mg/ha per year, so the total natural erosion rate is $0.1 + 0.05 = 0.15$ Mg/ha per year. In some areas, the natural rate may need to be increased to account for other natural processes, including soil creep, mass wastage, and bank erosion (Reid 2007). This number is sometimes referred to as the background erosion rate.

The second step in this type of watershed analysis is to consider the effects of the road network on current sediment delivery and the risk for future mass failure. This may be for two different conditions, the current condition with low-use or unmaintained roads, and the use condition, with maintained or upgraded roads. Some roads may be considered permanent features because of public demand, and they might be included with the background erosion rate.

The third step in this analysis is to consider the erosion associated with biomass removal from harvesting and any postharvest treatment activities. These erosion rates are divided by the frequency of the activity to compare with the background value.

The final step is to synthesize the results. All erosion estimates should be in the same units, such as tonnes from the watershed, tonnes per square kilometer, or tons per hectare. The effect of removing biomass for fuel may be a reduction of a wildfire risk and in the estimated erosion rate following the fire. Table 2 provides an example of synthesis. The US Forest Service Rocky Mountain Research Station has developed an online erosion prediction tool to conduct this type of synthesis (RMRS 2005). Additional sources of sediment from landslides, gullying, or channel erosion may be appropriate to include in some watersheds. Additional features, such as wetlands, lakes, other areas of deposition, water intakes, and fisheries resources, may be prominent in other watersheds, and the impacts of sedimentation on these beneficial uses of water need to be considered (Elliot and Audin 2006).

The typical values shown in Table 2 indicate that there may be a net decrease in sediment generation associated with biomass removal because the interval between severe wildfires is increased and the burn severity is estimated to be less. Recent observations have noted that wildfire intensity is likely to be reduced in areas that have had fuel reduction treatments compared with undisturbed forest with high fuel loads (Nakamura 2004, Graham et al. 2007, Murphy et al. 2007). The example in Table 2 is for a single hillslope only. A similar analysis is needed for all or a sample of all of the hillslopes that are to be accessed for biomass removal. There also are watershed analysis tools available that can assist with larger area analyses or in analyzing cumulative effects of biomass removal spanning a number of years on sites dispersed throughout a large watershed (Elliot and Audin 2006). The example presented in Table 2 is for sediment only. Managers may wish to carry out similar analyses for impacts of fuel management on runoff, wildlife, forest health, or recreation resources.

Summary

As society looks to our nation's forests as sources of energy, there is a risk of increased runoff and erosion. Compacting and displacing soil in forests and increased traffic on forest roads may increase runoff amounts and rates and soil displacement. Following well-established management practices can minimize these risks. When evaluating the risks of erosion associated with biomass use, managers should also consider erosion risk associated with wildfire, as that risk will decline as forest fuels are removed.

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